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CLIMATE IMPLICATIONS OF THE OBSERVED CHANGES IN OZONE VERTICAL DISTRIBUTION

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ABSTRACT

Satellite and ozone-sonde observations indicated a decreasing trend in the ozone concentration in the lower stratosphere and an increasing trend in the troposphere, especially the upper troposphere. We have used a one-dimensional radiative – convective model (RCM) to examine the climate implications of these observed changes in vertical distribution of ozone.

Instantaneous radiative forcing calculated by the one-dimensional radiative transfer model indicated a net warming of the surface–troposphere system due to stratospheric ozone losses. The increase in tropospheric ozone causes an additional positive forcing. However, the radiative forcing due to increases in trace gases during the same period is larger than the forcing due to ozone changes. There is marked decrease of the instantaneous solar and longwave heating rates in the lower stratosphere due to stratospheric ozone losses. Increases in tropospheric ozone causes additional decrease in longwave heating rate, in the lower stratosphere.

Consistent with the changes in the heating rates, the equilibrium temperature profile computed by the radiative–convective model predicted a cooling in the stratosphere of the order of 0·6°C and a very slight warming in the troposphere. The increase of tropospheric ozone causes an additional cooling in the stratosphere. The temperature decrease caused by ozone decrease in the lower stratosphere is larger than that caused by increase of trace gases concentration during the same period. The stratospheric cooling effect due to trace gases is, however, better presented near 30 km altitude.

KEY WORDS: ozone change; radiative forcing; stratospheric temperature trends

1. INTRODUCTION

Increases in concentration of atmospheric CO_2, N_2, CH_4 and chloroflurocarbons (CFCs) contribute to the atmospheric greenhouse effect. Their radiative effects on climate are well documented.

Ozone also plays a major role in determining the energy balance of the stratosphere and troposphere. It absorbs both solar and infra-red radiation. Ozone soundings in the Northern Hemisphere and SAGE I/II data indicate a decreasing trend in the lower stratosphere and an increasing trend in the troposphere especially the upper troposphere (Tiao *et al.*, 1986; Isakesen, 1988; Bojkov *et al.*, 1990; McCormick *et al.*, 1992; Quadrennial Ozone Symposium, 1992). Changes in the ozone vertical distribution can change radiative forcing with climate implications. Even though the net change in the column of ozone may be small, the vertical redistribution of ozone may produce a change in climate forcing, because the greenhouse efficiency of tropospheric ozone is greater than that of stratospheric ozone, as shown by Ramanathan *et al.* (1985) and Wang *et al.* (1988).

Ramaswamy *et al.* (1992) determined the radiative forcing of the surface–troposphere system due to the observed decadal stratospheric ozone losses and found a significant negative radiative forcing of the troposphere–surface climate system. Recently Mahlman *et al.* (1994) used a GFDL general circulation model to simulate the effect of the Antarctic 'ozone hole' phenomenon on the radiative and dynamical environment of the lower stratosphere. Miller *et al.* (1992), Lacis *et al.* (1990) and Schwarzkopf and Ramaswamy (1993) also addressed this problem.

Earlier estimates of climate impact caused by changes in ozone distribution have been made using one-dimensional photochemical models (Wang *et al.*, 1988; Ramanathan *et al.*, 1985). Recently, Wang *et al.* (1993)

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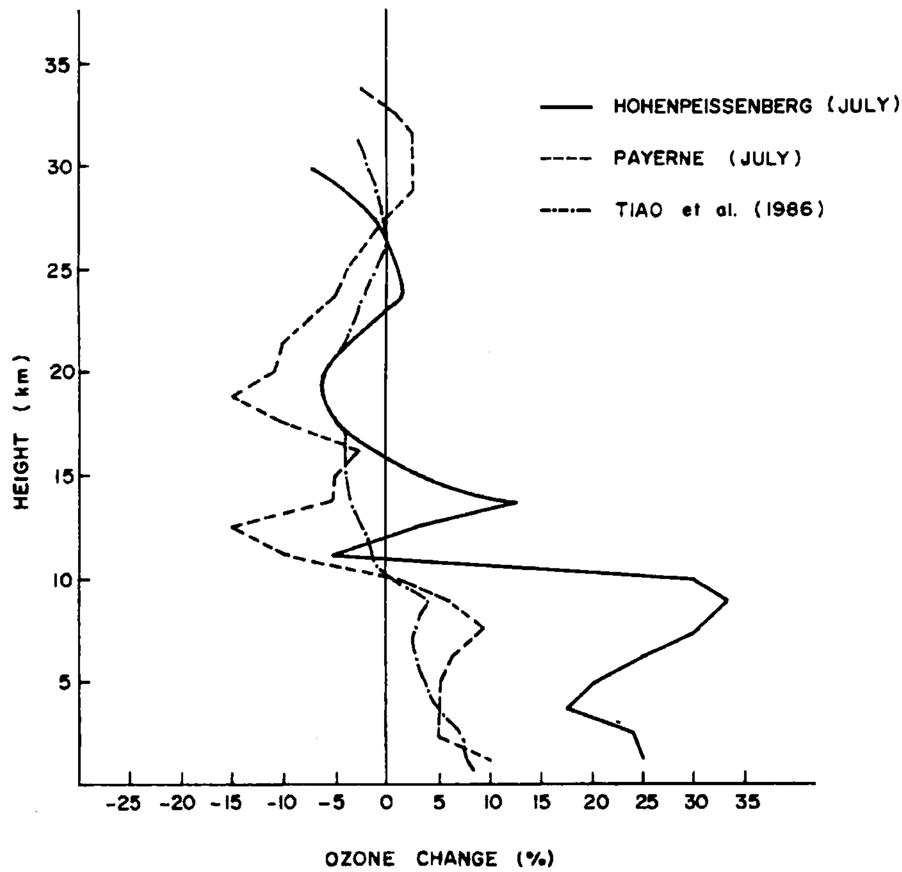

Figure 1. Observed percentage change of vertical distribution of ozone for Hohenpeissenberg (1970–1990), Payerne (1970–1990), and reported by Tiao *et al.* (1970–1982).

studied the ozone variations at seven stations and discussed the climate implications of these observed ozone changes using a radiative–convective model.

In this study we examine some aspects of the climate implications of observed changes in the vertical distribution of ozone using a one-dimensional radiative–convective model.

OBSERVED CHANGES OF VERTICAL DISTRIBUTION OF OZONE

Satellites provide the total column ozone amount and its stratospheric distribution above 25 km. Vertical distribution in the troposphere and stratosphere are measured using ozone-sondes. Long-term ozone-sonde data are available only at a limited number of stations in middle and high latitudes of the Northern Hemisphere.

The first statistically significant detection of long-term changes in the vertical distributions of ozone was reported by Angell and Korshover (1983). They analysed Umkehr and ozone-sonde measurements taken during the period 1970–1981 and found that tropospheric ozone had increased by 1·2 per cent year^{-1} within 2–8 km altitude range, and a 0·1–0·3 per cent year^{-1} decrease between 16 and 32 km.

Tiao *et al.* (1986) presented a detailed statistical trend analysis of ozone-sonde data from the northern mid-latitudes for the period 1970–1982. They included in their analysis sensitivity studies of trend estimates with respect to different correction procedures used to normalize ozone-sonde measurements. The trends derived by Tiao *et al.* were statistically significant in the troposphere and in the lower stratosphere when averaged over all the 13 stations.

Recently Wang *et al.* (1993) analysed the ozone data during the period 1970–1990 in respect of seven stations in mid- and high-latitudes of the Northern Hemisphere. They found that there is a trend of ozone decrease in the lower stratosphere and increase in the troposphere, especially in the upper troposphere.

In the present study we used ozone trends estimated by Wang *et al.* (1993) in respect of Hohenpeissenberg (47°N, 10°E) and Payerne (47°N, 7°E) and by Tiao *et al.* (1986) in order to examine their climatic implications. The ozone changes estimated by Wang *et al.* (1993) and Tiao *et al.* (1986) are shown in Figure 1.

There is trend of ozone decrease in the lower stratosphere and an increasing trend in the troposphere. At Hoehenpeissenberg, for example, stratospheric ozone decreased about 7 per cent around 20 km and tropospheric ozone increased 20–30 per cent between 5 and 8 km. Because the tropospheric ozone amount is about 10 per cent of the total column, the trend of the total ozone is dominated by stratospheric decreases. At Hohenpeissenberg the total ozone over the period 1970–1990 decreased at a rate of 2·3 per cent per decade. Results of Tiao *et al.* (1986) showed ozone increase in the lower stratosphere by about 0·5–1·0 per cent year^{-1} and ozone decreases 0·5 per cent year^{-1} in the upper troposphere and lower stratosphere.

RADIATIVE–CONVECTIVE MODEL

We have used the University of Illinois multilayer, one-dimensional radiative–convective model for this study. The one-dimensional radiative–convective model has 26 layers from the surface. The model is formulated from the thermodynamic energy equation.

$$\rho C_{\mathrm{p}} \frac{\partial t}{\partial z} = \frac{\partial S}{\partial z} - \frac{\partial R}{\partial z} + Q_{\mathrm{sfc}} + Q_{\mathrm{conv}}$$

where t is time, z is altitude, ρ is density, C_p is the heat capacity at constant pressure, S is the net downward solar radiation flux, R is the net upward longwave radiation flux, Q_{sfc} is the non-radiative transfer of energy from the surface to the atmosphere, and Q_{conv} is the convective redistribution of energy within the atmosphere.

Shortwave radiative calculations are based on the two-stream delta-Eddington method (Geleyn and Hollingsworth, 1979), using eight spectral intervals. The paramaterization for water vapour absorption is based on Chou and Arking (1981), ozone absorption on Lacis and Hansen (1974) and CO_2 by Fouquert (1988). The optical depth and single scattering albedo for cloud droplets are determined following Stephens (1978), for non-ice clouds, and Starr and Cox (1985), for cirrus clouds.

Longwave flux calculations are based on the two-stream formula of the flux equations with parameterized optical depths. Gaseous absorptions due to water vapour, CO_2, and ozone are considered. The parameterization of absorption of water vapour is based on Chou (1984) and Kneizys *et al.* (1983), CO_2 is based on Chou and Peng (1983), and ozone is based on Kneizys *et al.* (1983).

The model is integrated forward with a time step of 8 h, with convective adjustment to maintain a critical lapse rate limit (6·5°C/km). The model is integrated to bring the atmospheric temperature profile into radiative–convective equilibrium. In the radiative mode the one-dimensional model is used to determine the instantaneous changes in the radiative fluxes and heating rates due to changes in ozone profile.

We used climatological profiles of temperature and moisture and mid-latitude ozone distribution summaries given by McClatchy *et al.* (1972) as reference profiles. We also assumed clear-sky conditions and used climatological albedo values. The incoming solar radiation is varied according to the season.

MODEL RESULTS

Initial radiative perturbations

In order to investigate the climate implications of changes in ozone vertical distribution, we have calculated the instantaneous radiative forcing to the troposphere–surface system due to ozone changes in respect of Hohenpeissenberg, Payerne, and Tiao *et al.* To examine the relative importance of the ozone changes to those due to an increase in greenhouse gases, we have calculated forcing due to increases in the concentration of greenhouse gases from 1970 to 1990 as given in the IPCC report of 1990 (Houghton *et al.*, 1990). The results are

Table I. Instantaneous radiative forcing (W m^{-2}) for the troposphere – surface system due to ozone changes and increases in greenhouse gases between 1970–1990. The changes of Tiao *et al.* are from (1970 to 1982).

Case	Stratosphere	Total
Hohenpeissenberg:		
January	0·265	0·350
July	0·219	0·444
Payerne:		
January	0·127	0·184
July	0·150	0·191
Tiao *et al.*	0·077	0·161
Trace gases	0·765	

shown in Table I. We have calculated the forcing for stratosphere losses and the total (stratosphere plus troposphere) changes separately.

The effect of a decrease in stratospheric ozone for all cases is to cause a net warming of the troposphere-surface system. The increase of tropospheric ozone provides an additional forcing for all cases. For Hohenpeissenberg the effect of increases of tropospheric ozone dominate the total radiative forcing during July. However, for Payerne in July, because of the smaller values of tropospheric ozone increases, a small warming is calculated. For Hohenpeissenberg and Payerne, total radiative forcing dominates in July. The forcing due to stratospheric losses is more in January for Hohenpeissenberg and in July for Payerne. Comparatively smaller forcing is calculated for Tiao *et al.* case, obviously due to smaller ozone changes than at Hohenpeissenberg and Payerne.

In addition the instantaneous change in the heating rates produced by ozone changes are investigated by performing radiative calculations with the ozone trend profile of Tiao *et al.* (1986).

Figure 2 shows the solar, longwave and net heating rates. The effect of stratospheric losses on the heating rates also is investigated separately and shown in Figure 2.

There is a marked decrease of the solar heating rate in the lower stratosphere, peaking at 19 km. This is due to less photon absorption owing to loss of ozone. However, the tropospheric increases do not affect solar perturbations in the stratosphere or troposphere. The loss of stratospheric ozone also yields a decrease in longwave heating rates in the lower stratosphere, with a peak at 19 km. Above 20 km there is a positive (heating) perturbation. The increase in tropospheric ozone causes an additional decrease in the longwave heating rates in the lower stratosphere. Above 21 km, heating caused by the stratospheric losses is reduced by tropospheric ozone.

The net radiative heating perturbation (Figure 2 (c)) is the sum of individual perturbations shown in Figures 2(a) and 2(b). The net heating profile shows pronounced cooling, which is enhanced by tropospheric ozone over and above that produced by stratospheric losses only.

RCM equilibrium temperature changes

We have used the ozone trends calculated by Tiao *et al.* (1986) for estimating equilibrium temperature changes. Figure 3 shows the effect of changes in ozone on the equilibrium temperature profile computed by the RCM. We have also calculated the equilibrium temperature changes due to stratospheric ozone changes separately, and these are shown in Figure 3. Also shown in the figure are the atmospheric temperature changes that are expected for the increases in trace gases from 1970 to 1990.

The warming in the troposphere and the monotonic increase in stratospheric cooling with height are characteristics of CO_2 greenhouse effect. The increase in surface temperature was 0·56°C, and a cooling at 25 km was around −0·52°C.

Let us consider the case of stratospheric losses. Ozone decreases in the stratosphere causes cooling. The magnitude of the largest cooling in the stratosphere is about −0·5 K around at 18 km. The magnitude of the

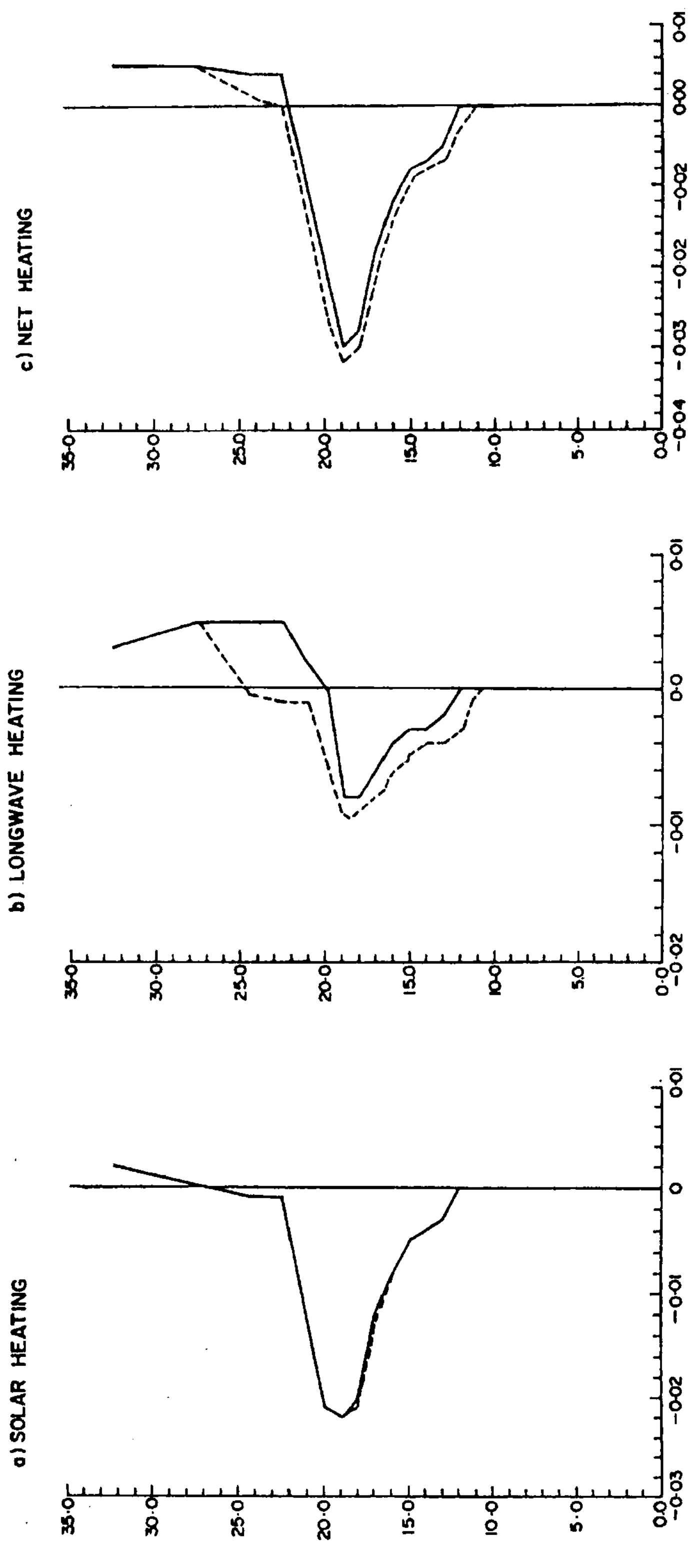

Figure 2. Change in the instantaneous (a) solar, (b) longwave, and (c) net heating rates due to the changes of stratospheric loss only (solid curve) and additional increase of tropospheric ozone (dotted curve:). The changes are for the trends estimated by Tiao *et al.* (1986).

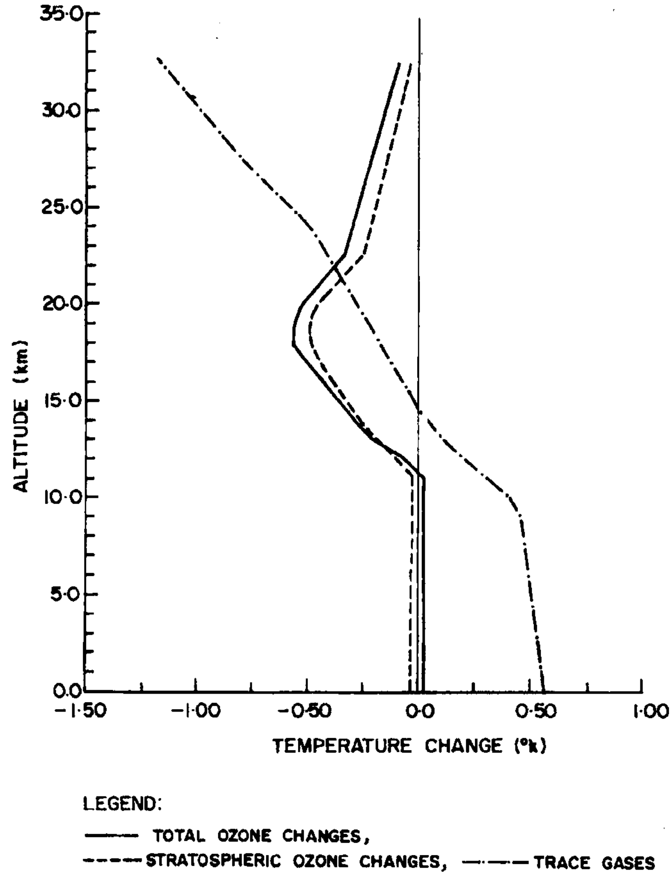

Figure 3. Equilibrium temperature changes calculated by the model for stratospheric losses and total changes estimated by Tiao *et al.* (1986) and for increase in trace gases from 1970 to 1990.

cooling below about 18 km decreases rapidly with decreasing height. Below 10 km a small uniform cooling throughout the region is obtained. This uniform temperature change in the troposphere, including the surface, results from the convective energy redistribution that is imposed by the lapse rate criterion. The critical lapse rate criterion has the effect of closely coupling the temperatures of tropospheric layers and the ground by means of convective heat exchange.

The cooling in the stratosphere is a result of reduction in the local absorption of ultraviolet solar energy due to ozone loss in the region. A decrease in temperature in the region can decrease the divergence of the downward longwave flux due to reduced emission. The reduced emission also causes a decrease of the longwave flux emitted into the troposphere, causing tropospheric cooling. The tropospheric cooling further reduces the upward flux into the stratosphere.

Now let us consider the case of ozone changes in the troposphere in addition to the stratospheric changes. In this case there is an enhancement of cooling in the lower stratosphere; for example, at 17 km the cooling is increased from $-0{\cdot}5$ K to $-0{\cdot}6$ K. The increases in tropospheric ozone cause a further cooling in the stratosphere and a warming in the troposphere, typical of ozone increases in the troposphere (Ramanathan and Dickinson, 1979; Wang *et al.*, 1993). Surface warming is of the order of 0·02°C.

Observed temperature changes

The cooling calculated for the observed ozone decrease is similar in magnitude to the observed temperature decreases measured by the radiosonde network at northern mid-latitudes. Angell (1986) reported decadal changes of −0·25°C for 9–16 km and −0·19°C for 16–20 km as the global average for the period 1970–1985. Parker (1985) shows a decrease of about 0·2°C for 1970–1980 at 20 km. Miller *et al.* (1992) estimated a positive trend of the order of 0·3°C per decade from the surface to 5 km range and a negative trend of about −0·4°C per decade at 16 km and 20 km. Oort and Liu (1993) infer a trend in the global lower stratospheric temperature of −0·4 ± 0·12°C per decade and the cooling trend indicated a temperature decrease of 0·44°C per decade in respect of Tiao *et al.* These stratospheric temperature decreases are suggestive of ozone decreases in the lower stratosphere. However, other physical factors, such as possible changes in the physical state of the troposphere, volcanic aerosols, change in the stratospheric circulation, etc., could also be contributing to the trends (Houghton *et al.* 1992).

CONCLUSIONS

Using a radiative-convective model, climatic implications of the observed changes in the vertical distribution of ozone are studied. Satellite and ozone-sonde observations indicated a decreasing trend in the ozone concentration in the lower stratosphere and an increasing trend in the troposphere, especially the upper troposphere.

Instantaneous radiative forcing calculated by the one-dimensional radiative transfer model indicated a net warming of the surface–troposphere system due to stratospheric ozone losses. The increase in tropospheric ozone causes an additional positive forcing. However, the radiative forcing due to increases in trace gases during the same period is larger. There is marked decrease of the instantaneous solar and longwave heating rates in the lower stratosphere due to stratospheric ozone losses. Increase in tropospheric ozone causes an additional decrease in longwave heating rate in the lower stratosphere.

The equilibrium temperature profile computed by the radiative–convective model predicted a cooling in the stratosphere of the order of 0·6°C and a very slight warming in the troposphere. The increase of tropospheric ozone causes an additional cooling in the stratosphere. The temperature decrease caused by an ozone decrease in the lower stratosphere is larger than that caused by an increase in trace gas concentration during the same period. The stratospheric cooling effect due to trace gases is, however, better presented near 30 km altitude.

The problem of climate forcing by changes in the vertical distribution of ozone requires further modelling and observations. The observations are required for defining trends in the upper troposphere and lower stratosphere at low latitudes and in the Southern Hemisphere. We should have a global data base for the vertical distribution of ozone, and the nature of the problem requires the measurement capability of satellites.

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